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Determination of Ice Cohesion in VEPC Constitutive Model for Sea Ice Dynamics

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A viscoelastic-plastic with cohesion (VEPC) constitutive model is established during dynamics numerical simulation of Bohai sea ice, however, how to determine the expression of cohesion is the key problem. Therefore, through direct shear test of sea ice specimens in laboratory, the experiment relation data of shear strength with temperature and salinity are obtained. On the basis of data the bi-parameter-function of cohesion with temperature and salinity is determined. The above work further improves the VEPC constitutive model, which leads to its better use in numerical stimulation of sea ice.
Keywords: sea ice, cohesion, temperature, salinity, direct shear test

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1. Introduction

Bohai sea is an important sea economic zone of China, in which the activities of oil and gas development and ice shipping are growing in frequency. But the existence of the Bohai sea ice has a significant impact on the economic activity of Bohai sea and the sea ice disaster due to the existence of the sea ice is becoming more and more concerned by people. In order to study the dynamic movement of sea ice, many studies in sea ice dynamics was proceed, in which a small-scale sea ice dynamics of viscoelastic-plastic constitutive model was established (Ji shunying, 2005). They simulate the Bohai sea ice using this model and the results of the simulation show that the constitutive model has good reliability.

However, because the influencing factors are so many that how to determine its expression has always been a difficult problem in this model. According to this, this paper first obtains the function of the cohesion with the temperature and salinity of sea ice through theoretical analysis and obtains test data of shear strength and temperature of sea ice through direct shear test of sea ice in laboratory and then obtains the specific expression of cohesion by fitted test date with the theory function of cohesion.

2. The Mohr-Coulomb Yield Criterion

In the σ-τ plane (as Fig.1), the Mohr-Coulomb criterion can be showed as

$$\tau_n = c + \sigma_n \tan\varphi \quad \textbf{[1]}$$

where, τ_n and σ_n are the shearing stress and normal stress in the shear plane, respectively; c is the cohesion, its value is equal to intercept of the yield criterion on the vertical axis, the c was determine by direct shear test; φ is the friction angle.

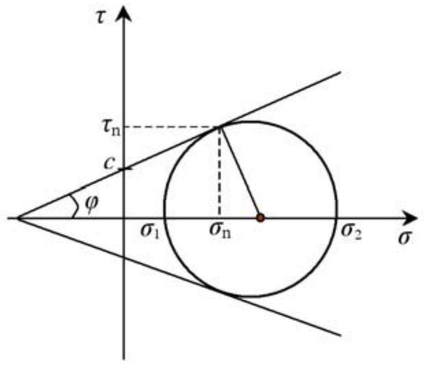

Figure 1. Mohr-Coulomb yield criterion.

3. Determination of the Theory of Cohesion

3.1 one-parameter model of cohesion with temperature

The relationship between the cohesion with temperature is used as (Fish, 1997)

$$c(T) = c_0[1 + \alpha(1 - T/T_m)] \quad \textbf{[2]}$$

$$c(T) = c_0 e^{\alpha(1 - T/T_m)} \quad \textbf{[3]}$$

where, T_m is melting temperature of sea ice which means 0℃ to pure ice; c_0 is cohesion component generated at the beginning of formation of ice; a is characteristic parameter.

And Vyalov (1996) also obtain the following equation to describe the relationship between temperature with cohesion

$$c(T) = c_0 + b\sqrt{|T|} \quad \textbf{[4]}$$

where, b is an empirical constant. It is observed that the cohesion and shear strength of sea ice form a linear relationship From Eq. [1]. But the nature of cohesion is also a kind of performance of strength of the sea ice. The relationship of cohesion with temperature was assumed a linear relationship that

$$c = a + d \cdot T \quad \textbf{[5]}$$

where, a and d are undetermined constants which can be determined by direct shear test of sea ice.
3.2 one-parameter model of cohesion with salinity
In the research of Bohai sea ice, based on the statistics of field test of Bohai the relationship between shear strength and porosity of sea ice was obtained (Li Zhijun, 2002, 2006)

$$\tau = 16.47 v^{-0.6826} \text{ (MPa)} \quad \textbf{[6]}$$

where v is porosity, it can be used brine volume v_b instead (Frankenstein, 1967)

$$v_b = S_i (0.532 - \frac{49.185}{T}) \quad [-0.5℃ \geq T \geq -22.9℃] \quad \textbf{[7]}$$

And Ji Shunying (2013) also obtain similar equation

$$\tau = 0.18 v^{-0.4} \text{ (MPa)} \quad \textbf{[8]}$$

But the strength described in the Eq. [6] to Eq. [8] is referring to the mechanical property of sea ice within the scope of the laboratory and tiny scales. Zhang (2000) indicate that moving sea ice has different material property at different spatial scales. For the broken sea ice floating on the sea different broken ice has different mechanical property. So the mechanical parameter of sea ice is referring to parameters in the average small-scale state. This needs to establish the connection between different sea ice mechanical properties under different scales. Lepparanta (1998) provides a simple proportional relation between the stress state and scale $\boldsymbol{\sigma} \propto L^{-0.5}$.So we assume that the small-scale mechanics parameters of Sea ice and the Eq. [6] to Eq. [8] have the same functional form. Hence, the Power function form of cohesion is represented as follows:

$$c = f\sqrt{S_i}^{\,g} \quad \textbf{[9]}$$

In the equation, f and g are empirical constant which can be obtained from the straightway testing of sea ice.

3.3 two-parameter fracture model of cohesion with temperature and salinity

In order to analyze the coupling effect of temperature and salinity to cohesion can assume cohesion and T and Si have the following relation according to the single factor influence of cohesion with temperature and salinity, the linear relation of cohesion with temperature, the power function relation with salinity and the function relationship referred to the Eq. [5] to Eq. [9]

$$c = (m + nT)e^{(p+qT)\sqrt{S_i}} \quad \textbf{[10]}$$

where, m、n、p and q are fitting parameters in the equation.

4. Direct Shear Test

In the laboratory, the test data of sea ice specimen was obtained by confined single face shear test. And the cohesion of sea ice and internal friction angle also could be obtained by the test method (Whillans, 2001). What's more, heat preservation and temperature control measures are necessary for the sake of obtaining the congruent relationship between sea ice temperature with shear strength.

Used two thick steel plates in the test to constrain the lateral expansion of ice under shear loading, to prevent the tensile stress at the bottom of the ice sample and to overcome the bending failure in order to get the assured veracity. Pressure direction collects the direction of shear force and the size of the displacement. Loading mode of shear test and test systems is shown as Fig.2. After shear failure the sea ice specimen is shown as Fig.3.

The pressure and displacement of pressure head are acquired by computer during the test. At the same time, the temperature and salinity of sea ice are measured and recorded. The calculate the shear strength of sea ice can accord to the shear strength equation of material mechanics

$$\tau_f = \frac{T_{\max}}{th} \quad \textbf{[11]}$$

where, $T_{\max}$ is the maximum load when sea ice shear failure; t and h are long and wide of stressed area, respectively.

Figure 2. Sea ice shear test systems.

Figure 3. Sea ice shear failure.

The sea ice sample used in the test systems respectively from three monitoring area of sea ice from the Bohai bay. The size of sea ice specimen is 90cm×90cm×50cm and 90cm×88cm×50cm and the area of shear plane is 90cm×50cm and 88cm×50cm. The temperature of sea ice is controlled from -1℃ to -10℃ according to the test requirements forming the temperature gradient of sea ice , while was obtained the salinity of every ice specimen. About 49 group of sea ice specimen are totally tested.

5. Data fitting

Finally the functional form of sea ice cohesion was determined through the theoretical research and direct shear test in laboratory.

5.1 one-parameter model of cohesion with temperature

The experimental data and fitted curve of the cohesion with temperature are shown in Fig.4. The relation of sea ice cohesion with temperature through the sea ice direct shear test was obtained

$$c = 0.8324 - 0.0693T \quad \textbf{[12]}$$

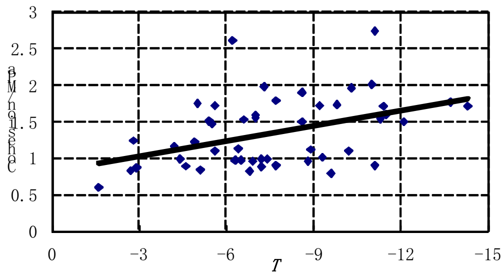

Figure 4.cohesion with temperature.

5.2 one-parameter model of cohesion with salinity

Through the shear strength test of sea ice, the experimental data and fitted curve of the cohesion with salinity are shown in Fig.5. The relation of sea ice cohesion with salinity through the sea ice direct shear test was obtained

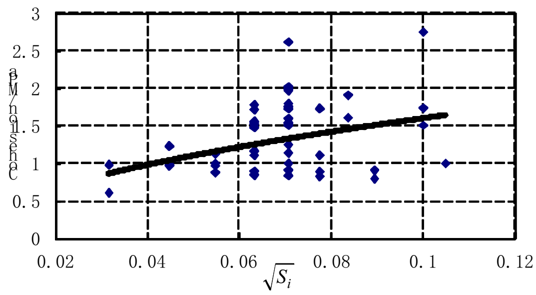

Figure 5. Cohesion with salinity.

And the function relationship of cohesion with salinity through numerical simulation is

$$c = 5.506\sqrt{S_i}^{0.536} \quad \textbf{[13]}$$

5.3 two-parameter fracture model of cohesion with temperature and salinity

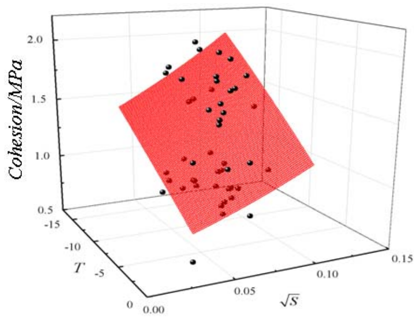

Figure 6. Cohesion with temperature and salinity.

The experimental data and fitted curve of the cohesion with temperature and salinity are shown in Fig.6. Through the data fitting, and connecting with the Eq. [10], the function of cohesion of sea ice with temperature and salinity was obtained

$$c = (0.63 - 0.045T)e^{(5.33+0.06T)\sqrt{S_i}} \quad [14]$$

6. Conclusions

Cohesion is an important influencing parameter in the constructive model of VEPC. There is not a definite function all the way because of so many influencing factors. This article provides the functional relationship of cohesion with temperature and salinity according to the influencing parameters to cohesion, the temperature of sea ice and salinity. Also, it provides a corresponding function equation of cohesion with temperature and salinity through fitting analysis in which the results shows the cohesion sea ice form a linear relationship with temperature and a power function relationship with salinity in the one-parameter model. At the same time two-parameter model of cohesion with temperature and salinity also was established. The above work further improves the VEPC constitutive model, which leads to its better use in numerical stimulation of sea ice.

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